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Investigating the diameter of solid particles effects on a laminar nanofluid flow in a curved tube using a two phase approach

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ABSTRACT

In this paper, we report the results of our numerical studies on laminar mixed convection heat transfer in a circular Curved tube with a nanofluid consisting of water and 1 vol.% Al_2O_3. Three dimensional elliptic governing equations have been used. Two phase mixture model and control volume technique have been implemented to study flow field. Effects of the diameter of particles on the hydrodynamic and thermal parameters are investigated and discussed. Increasing the solid particles diameter decreases the Nusselt number and secondary flow, while the axial velocity augments. When the particles are in order of nano meter, increasing the diameter of particles, do not change the flow behaviors. The distribution of solid nanoparticles is uniform and constant in curved tube.

1. Introduction

In recent years, modern technologies have permitted the manufacturing of metallic particles down to the nanometer scale, which in turn created a new class of fluids, called nanofluids. This term refers to a two phase mixture that is usually composed of a saturated liquid and extremely fine metallic particles (40 nm or smaller) called nanoparticles.

It has been known that the thermal conductivity of these nanofluids is considerably higher than that of the base fluid (Masuda et al., 1993; Choi, 1995; Lee et al., 1999). The nanofluids constitute a very interesting alternative for advanced thermal applications, in particular in micro and nano scale heat transfer where a high heat flux is required (Lee and Choi, 2000). In spite of their interesting potential and features, these rather special fluids are still in their early development stage. The very first and scarce experimental works were mostly concerned with the measurement of the nanofluids effective thermal conductivity and dynamic viscosity (Masuda et al., 1993; Choi, 1995; Lee et al., 1999; Pak and Cho, 1998; Wang et al., 1999; Eastman et al., 1999, 2001; Xuan and Li, 2000). Das et al. (2003) and Putra et al. (2003) were likely the first who investigated the influence of temperature on nanofluid thermal properties. Their measurements for a water–Al_2O_3 mixture, although limited to two particular particle concentrations (e.g. 1% and 4%), have clearly shown that with an increase of temperature the effective thermal conductivity augments considerably. On the other hand the dynamic viscosity decreases appreciably, which is quite interesting for potential uses of nanofluids in various thermal applications. The experimental works by Pak and Cho (1998), Li and Xuan (2002) and Wen and Ding (2004) have provided interesting insights into the hydrodynamic and thermal behavior of nanofluids in confined flows and have confirmed their superior thermal performance. These results led to the first empirical Nusselt number correlations for both laminar and turbulent tube flow of nanofluids composed of water and metallic particles such as Cu, TiO_2 and cAl_2O_3. In their most recent work, Yang et al. (2005) have measured the convective heat transfer coefficients of several nanofluids composed of graphitic nanoparticles and automatic transmission fluid. Results from these pioneer works have clearly shown that the inclusion of dispersed particles produces a remarkable increase of the heat transfer flux since the convective heat transfer coefficient of the nanofluids for a given Reynolds is, in general, considerably higher than the corresponding one for the base fluid (saturated water). This improvement increases with an augmentation of the particle loading.

Numerous theoretical and experimental studies have been conducted to determine the effective thermal conductivity of nanofluids. Most of these have been confined to liquids containing micro and milli-sized suspended solid particles. However, studies show that the measured thermal conductivity of nanofluids is much larger than the theoretical predictions (Choi et al., 2001). Many attempts have been made to formulate efficient theoretical models for the prediction of the effective thermal conductivity,

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Nomenclature

a	radius of curved pipe (m)
a	acceleration (ms^{-2})
C_p	specific heat (J/kg K)
d	horizontal direction
D	diameter of curved tube (m)
De	Dean number ($= Re \cdot \delta^{1/2}$)
f_θ	local skin friction coefficient
g	gravitational acceleration ($\mathrm{m\,s^{-2}}$)
Gr	Grashof number $\left(= \frac{g\beta_m q'' D^4}{k_m \upsilon_m^2}\right)$
Nu_θ	local Nusselt number $\left(= \frac{q'' D}{k_m (T_w - T_b)}\right)$
P	pressure (pa)
Pr	Prandtl number $\left(= \frac{\alpha_m}{\nu_m}\right)$
q''	uniform heat flux ($\mathrm{W\,m^{-2}}$)
R_c	curvature radius
Re	Reynolds number $\left(= \frac{\rho_m V_0 D}{\mu_m}\right)$
T	temperature (k)
V	velocity ($\mathrm{m\,s^{-1}}$)
y	vertical direction

Greek symbols

α	thermal diffusivity
β	volumetric expansion coefficient (K^{-1})
δ	curvature ratio ($= a/R_c$)
λ	thermal conductivity (W/m K)
θ	angular coordinate in axial direction
ϕ	volume fraction
μ	dynamic viscosity ($\mathrm{N\,s\,m^{-2}}$)
v	kinematics viscosity ($\mathrm{m^{-2}\,s^{-1}}$)
ρ	density ($\mathrm{kg\,m^{-3}}$)

Subscripts

0	inlet condition
b	bulk
f	base fluid
m	mixture
p	particle
r	radial direction
s	solid phase
w	wall
z	axial direction
φ	tangential direction

but there is still a serious lack in this domain (Xue, 2003; Xuan et al., 2003).

Convective heat transfer with nanofluids can be modeled using the two phase or single phase approach. The first provides the possibility of understanding the functions of both the fluid phase and the solid particles in the heat transfer process. The second assumes that the fluid phase and particles are in thermal equilibrium and move with the same velocity. This approach is simpler and requires less computational time. Thus it has been used in several theoretical studies of convective heat transfer with nanofluids (Maige et al., 2004a,b; Roy et al., 2004; Khanfar et al., 2003; Akbarinia and Behzadmehr, 2007; Akbarinia, 2008). However, due to the fact that the effective properties of nanofluids are not known precisely, the numerical predictions of this approach are, in general, not in good agreement with experimental results. Therefore, the concerns in single phase modeling consist in selecting the proper effective properties for nanofluids and taking into account the chaotic movement of ultra fine particles. To partially overcome this difficulty, some researchers (for instance, Xuan and Li, 2000; Xuan and Roetzel, 2000) have used the dispersion model which takes into account the improvement of heat transfer due to the random movement of particles in the main flow. Recently Behzadmehr et al.(2006) have used the mixture model with turbulent nanofluid flow. They have shown that the mixture model can predict behaviors of nanofluid accurately.

Due to several factors such as gravity, friction between the fluid and solid particles and Brownian forces, the phenomena of Brownian diffusion, sedimentation, and dispersion may coexist in the main flow of a nanofluid. This means that the slip velocity between the fluid and particles may not be zero (Xuan and Li, 2000), therefore it seems that the two phase approach is better model to apply the nanofluid. The two phase approach is based on an assumption of continuum phases. It provides a field description of the dynamics of each phase (Eulerian–Eulerian or two fluid model) or, alternatively, the Lagrangian trajectories of individual particles coupled with the Eulerian description of the fluid flow field (Fan and Zhu, 1998; Gidaspow, 1994). One of the foremost approaches in modeling two phase slurry flow is mixture theory, also called the theory of interacting continua (Ishii, 1975; Crowe et al., 1996; Manninen et al., 1996; Xu et al., 2004). The popularity of this latter approach in multiphase applications stems from the fact that it is simple in both theory and implementation. The required computations are relatively inexpensive. Furthermore, it is straight-forward to introduce a turbulence model into the mixture model, and most of all, it is reasonably accurate for a wide range of two phase flows.

In this paper, a two phase mixture model was applied to study the laminar mixed convection of a nanofluid flow consisting of water–Al_2O_3 in a uniformly heated curved tube. Affects of magnitude of solid particles on thermal and hydrodynamic flow characters are investigated and presented.

2. Mathematical formulation

2.1. Mixture model

Laminar mixed convection of a nanofluid flow consisting of water and Al_2O_3 in a horizontal curved tube with uniform heat flux at the solid–liquid interface has been considered. Fig. 1 shows the geometry of the considered problem. The computation domain is composed of a curved circular pipe where the axial angle θ ranges from 0° to 180°, with radius a and sectional angle φ which curvature ratio δ is equal to $\frac{1}{12}$. Gravitational force is exerted in the vertical direction. The properties of the fluid are assumed constant except for the density in the body force, which varies linearly with the temperature (Boussinesq's hypothesis). Dissipation and pressure work are neglected.

The mixture model, based on a single fluid two phase approach, is employed in the simulation by assuming that the coupling between phases is strong, and particles closely follow the flow. The two phases are assumed to be interpenetrating, meaning that each phase has its own velocity vector field, and within any control volume there is a volume fraction of primary phase and also a volume fraction of the secondary phase. Instead of utilizing the governing equations of each separately, the continuity, momentum and energy equations for the mixture are employed. A nanofluid composed of water and Al_2O_3 nanoparticles flowing in a curved tube with uniform heating at the wall boundary is considered. Therefore, the dimensional equations for steady state mean conditions are as follow: